STELLAR CONVECTION IN LATE-TYPE GIANTS AND SUPERGIANTS

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1. Convection in the Sun and stars

2. Stellar Dynamos

3. Solar and stellar activity

4. Stellar surface structure

5. Potential for interferometric observations

"CLASSICAL" CONVECTION

Schwarzchild criterion for convective instability

$$\left|\frac{dT}{dr}\right| > \left|\left(\frac{dT}{dr}\right)\right|_{abia\cancel{ta}batic}$$

BOHM-VITENSE (1958, Zs. f. Ap 46, 108)

Mixing length $\alpha = \dfrac{L_{ML}}{H_P}$ — mixing length / — pressure scale height $\qquad \alpha \approx 1.6$

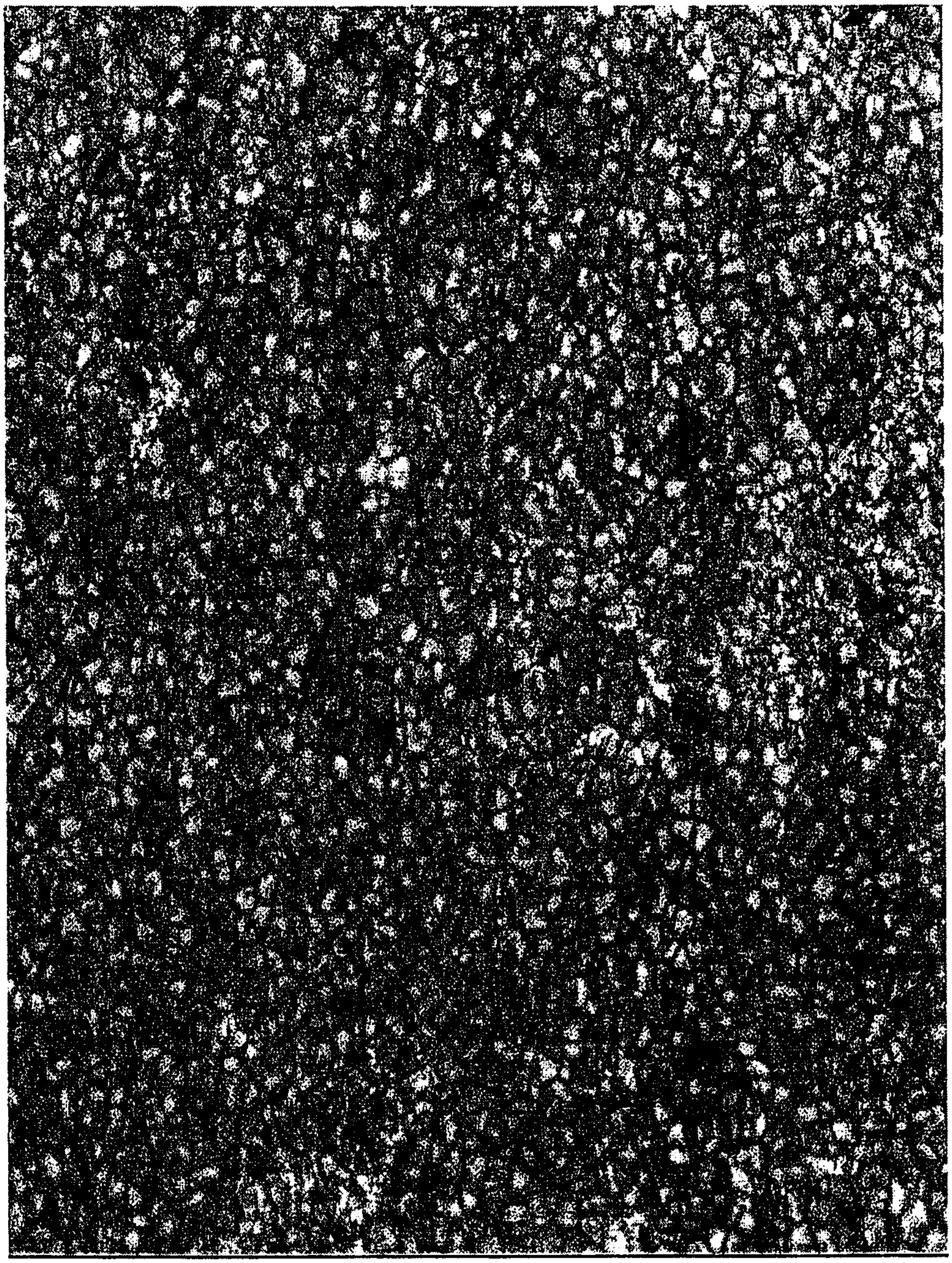
Convective flux density

$$F_C \simeq \frac{5}{\alpha}\, \rho(r)\, \hat{v}^3(r) \qquad \equiv \sigma T_{eff}^4 \frac{R^2}{r^2}$$

if convection is only transport mech.

Radiative flux density

$$F_R = -\frac{16\sigma T^3}{3\kappa_R \rho}\frac{dT}{dr}$$



SOLAR CONVECTION ZONE — IN CONTEXT

$R_\odot \sim 700$ Mm

Core ~ 100 Mm

50% of mass $R < 175$ Mm

Radiative Zone ~ 500 Mm

$[R = 0.71 - 1.0 R_\odot]$ Convection Zone $500 \rightarrow 700$ Mm 2/3 volume 2% of mass

Photosphere $\approx$ few $\times 10^2$ m thick

Chromosphere ~ 10 Mm thick

Corona — many scales $(0.1 R_\odot - 1 R_\odot)$

Solar Wind $\gg 1$ AU.

CONVECTION IN OTHER STARS

Models at use mixing length theory

→ stellar structure models

→ stellar evolution models

"Cool stars" ≡ those with convection zones just below photosphere

Thin convection zone ~ late A / early F stars

Fully convective – mid M stars

KM Giants / Supergiants – deepenning CZ

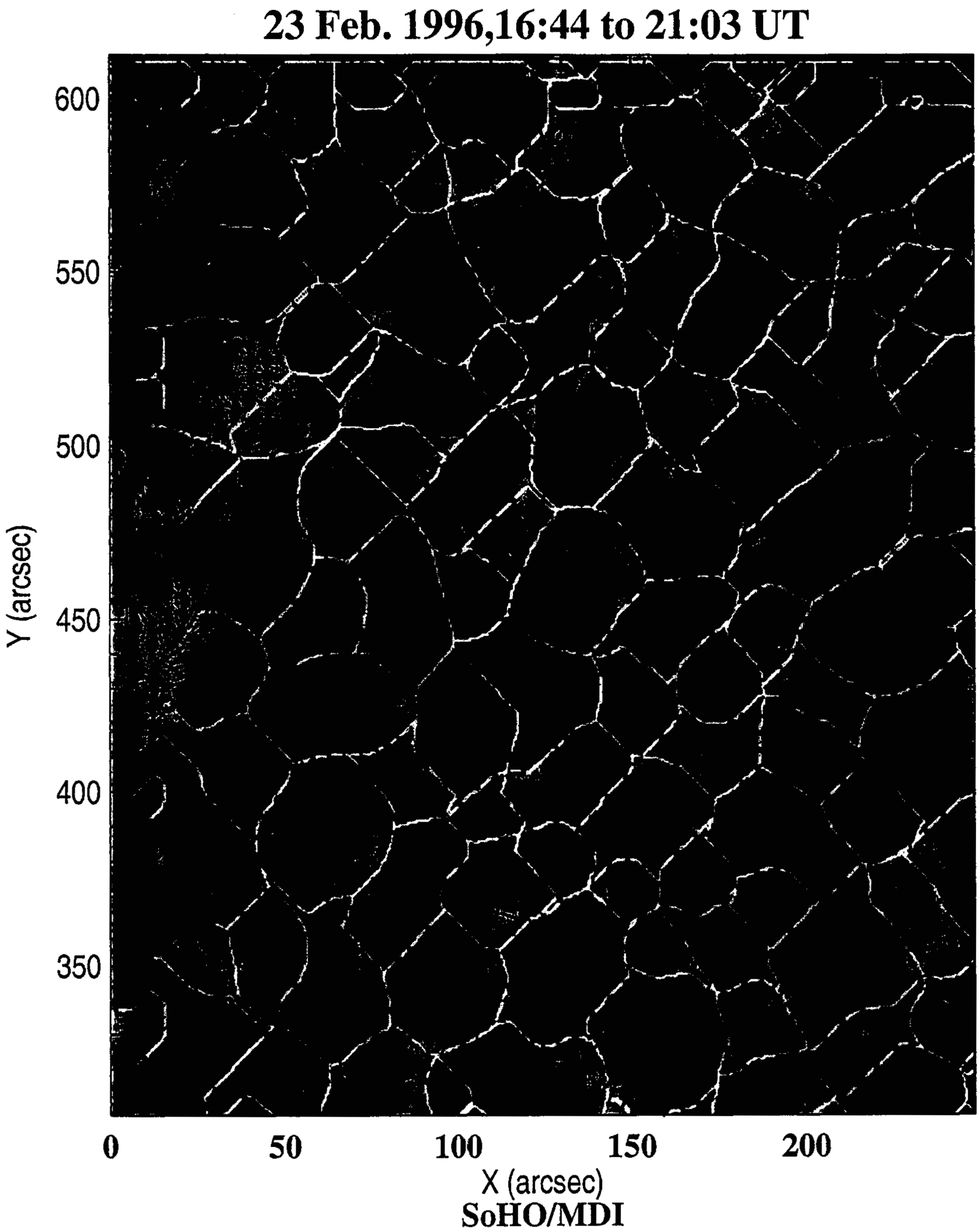
– convective mixing

[Evolution models need convective overshoot]

Solar Supergranulation and Surface Flows

High resolution SOHO - MDI magnetogram overlaid with lines of convergence of the photospheric horizontal flows.

- Measured flow shown as colored arrows; red = downflow, blue = upflow.
- Green dots mark the convergence points.
- Magnetic field; light grey for positive fields, for negative fields.



NUMERICAL 3-D MHD SIMULATIONS OF SOLAR CONVECTION

Work of e.g. Nordlund, Stein, Dravins,
Toomre, Brummel

[Abinitio 3D MHD – field equations, radiative transfer, atomic physics

Heroic effort – new insights into how convection operates in outer few pressure scale heights of Sun

They find – upward and downward moving elements do NOT mix.

– circulation driven by cooling at surface NOT by buoyant bubbles.

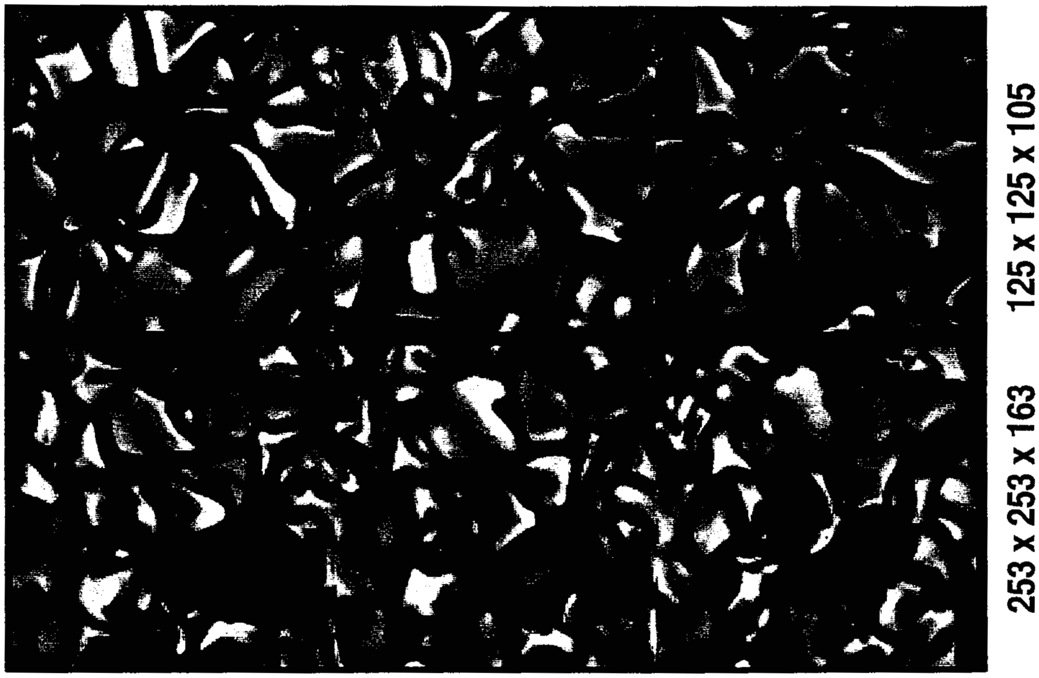
– large upflow areas feed strong downdrafts.

Flow scales: ~ 10 min at top of CZ, ~ 1 month at bottom of CZ

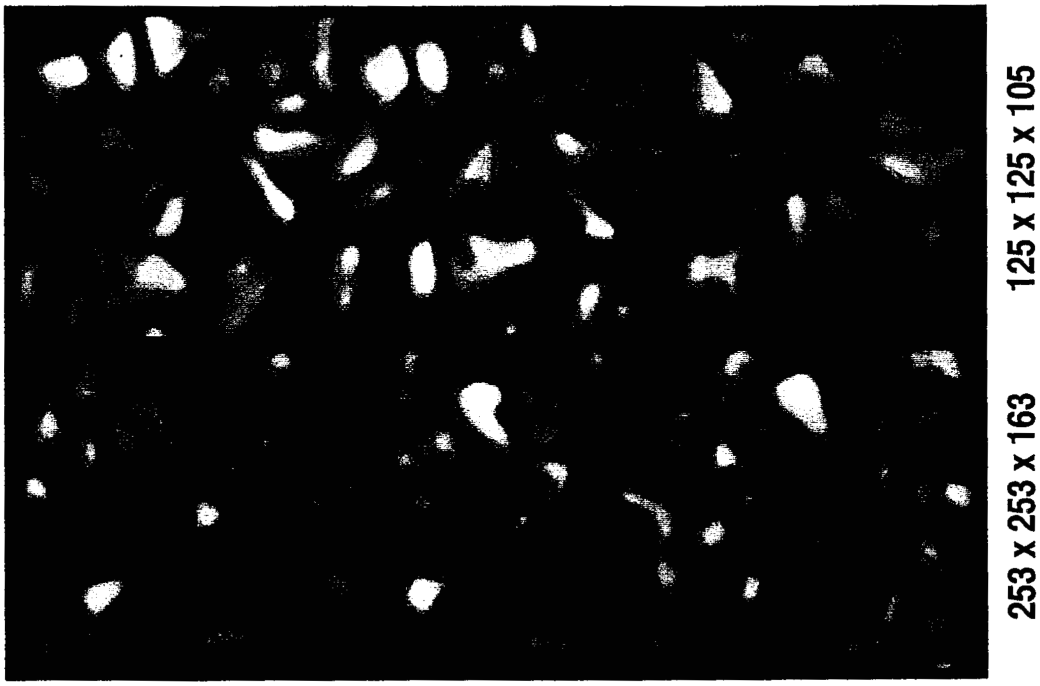
Excellent match to temperature and velocity fields, photospheric absorption line profiles. Also fit p modes

Full problem still too hard
Density range 10^6, pressure range 10^9

surface brightness; 3–dimensional simulations



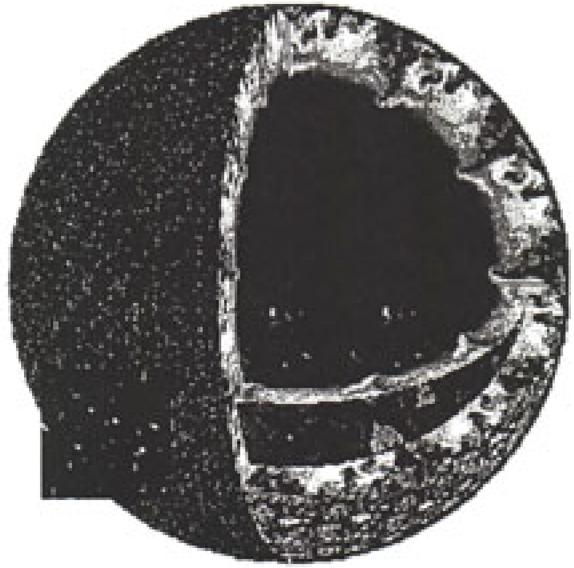
as above, simulated 40 cm telescope & atmosphere



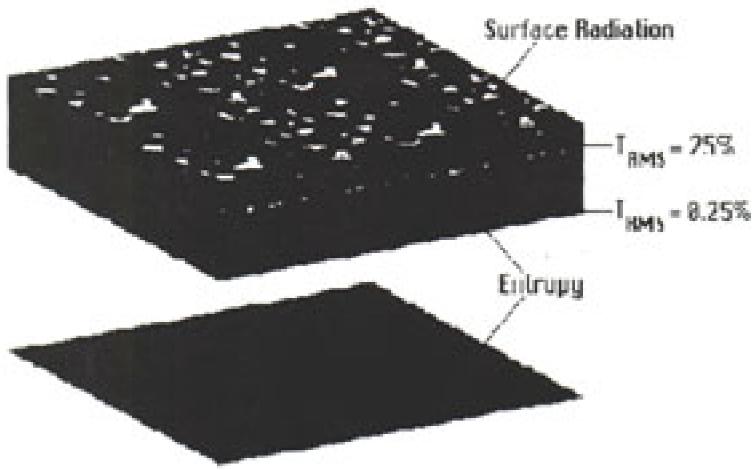
observations, Swedish 40 cm @ La Palma

Solar Convection

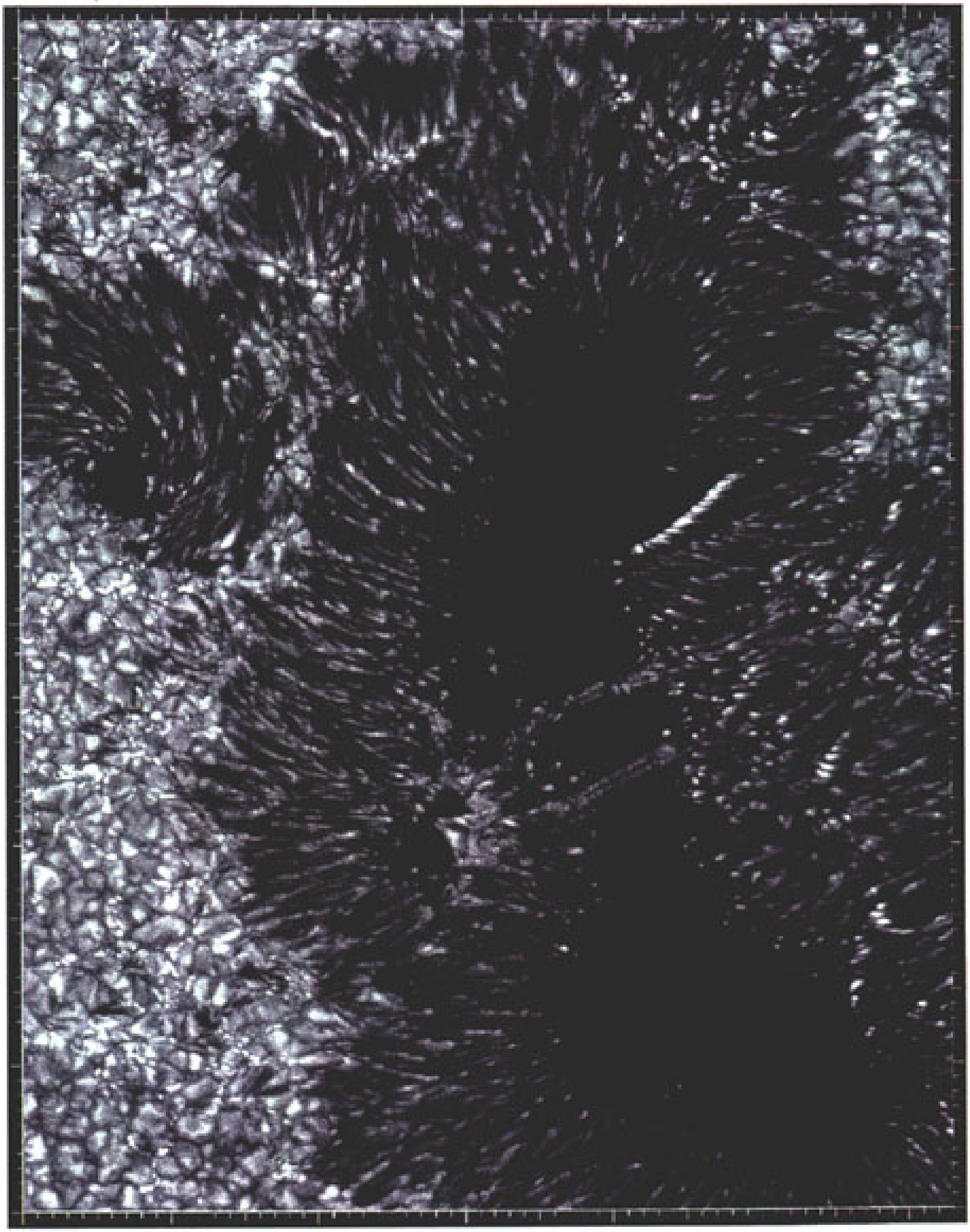
- **Global / Convection Zone**
  - Inner 3-4 orders of magnitude in density
    - 95% of CZ depth
  - Scales of the order of CZ depth
  - Turn-over times ~ months
  - Polytropic stratification
    - index ~ 3/2, nearly ideal



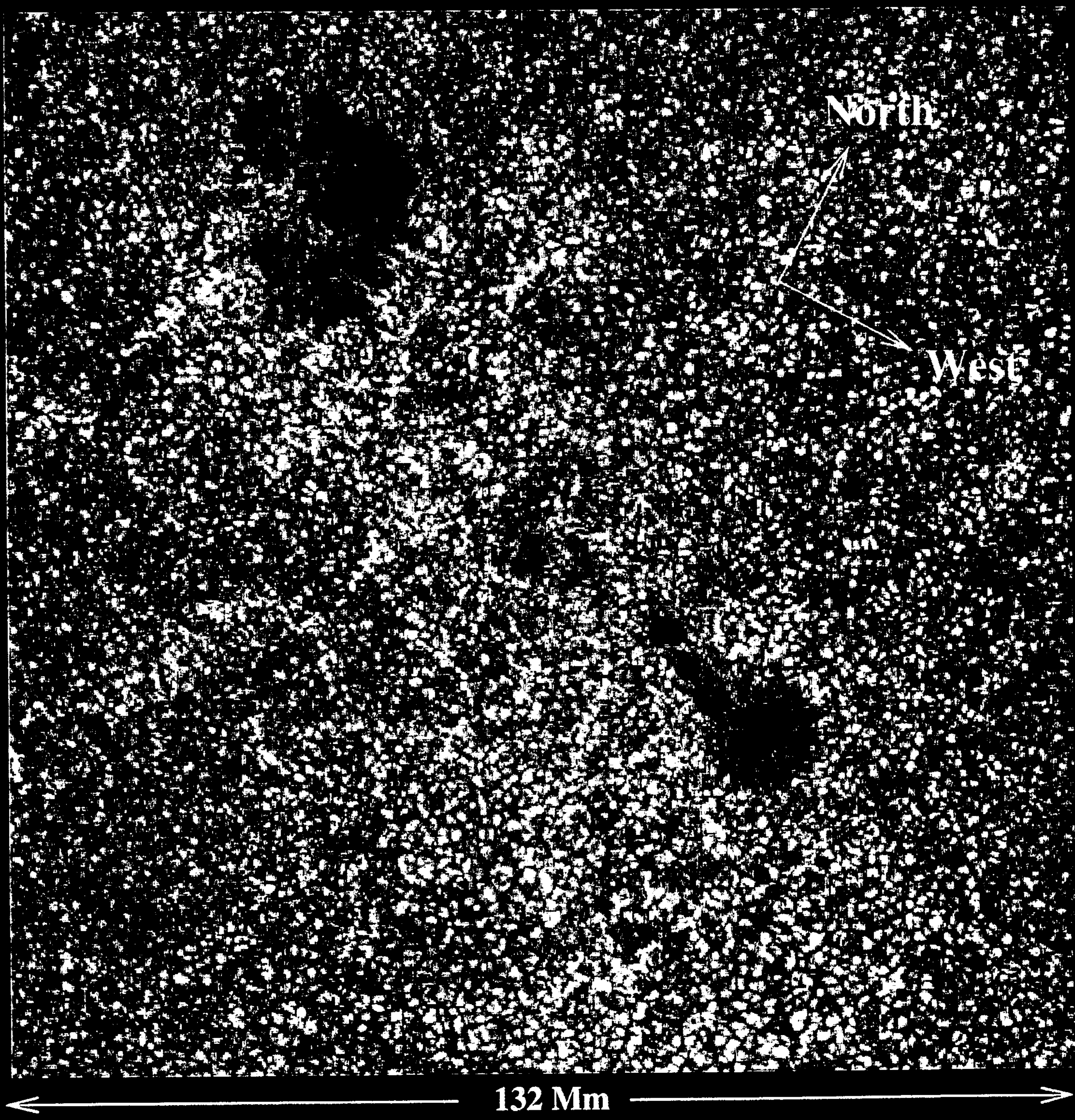
- **Surface layers**
  - Outer 4-6 orders of magnitude in density
    - 5% of CZ depth ~ 10 Mm
  - Scales from several x 10 Mm to below 1 Mm
  - Turn-over times from days to minutes
  - Stratification: ~exponential
    - polytropic with large index



Fortunately, life is more interesting ......



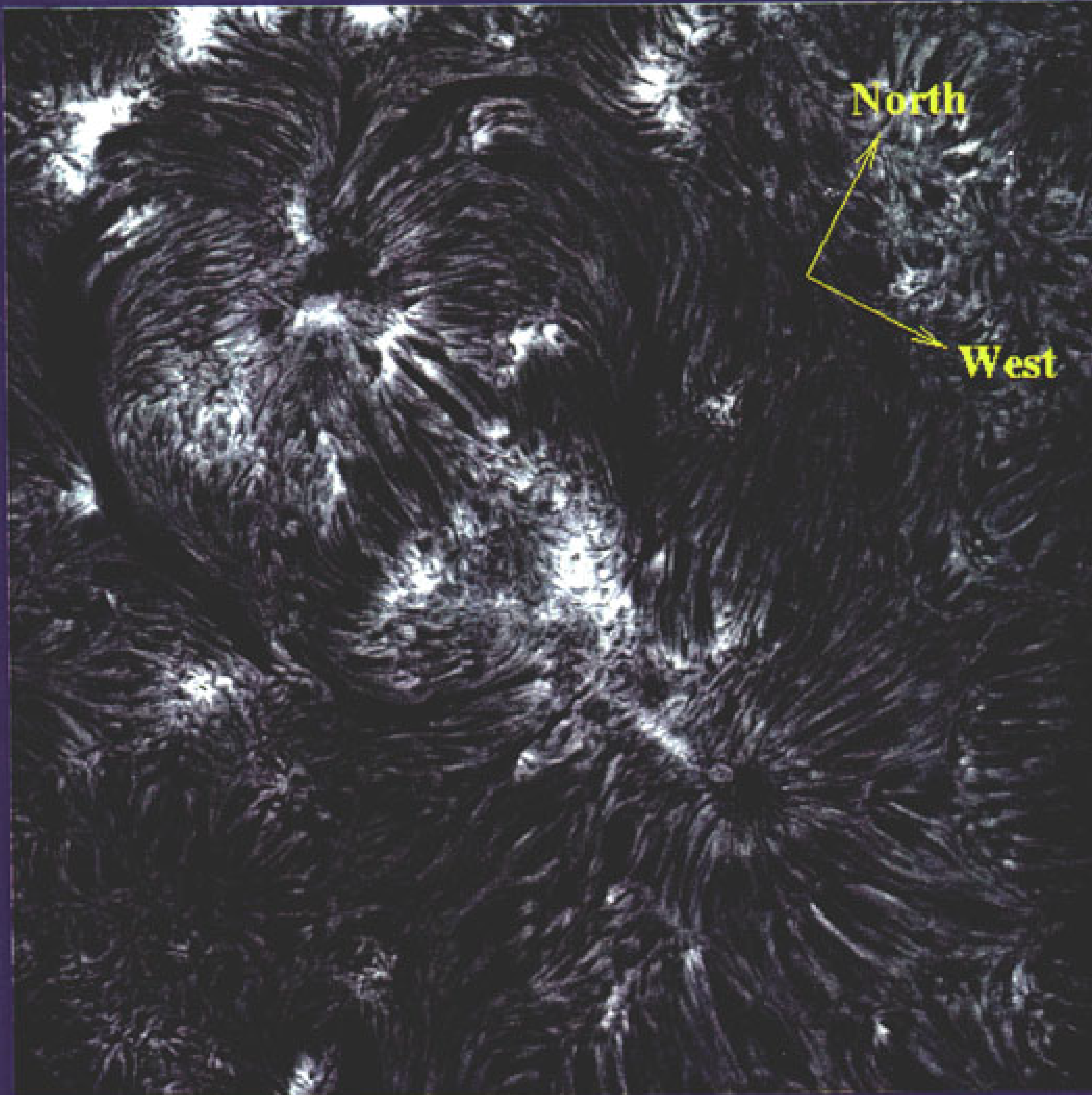
G Band - Swedish Vacuum Solar Telescope, La Palma, Spain.



G-Band **AR 9037, 14 June 2000, 10:00 UT**

Swedish Vacuum Solar Telescope, La Palma, Spain

L. Strous, D. Torgerson, Stanford Lockheed Institute for Solar Research



135 Mm

Hα Line Center **AR 9037, 14 June 2000, 10:00 UT**

Swedish Vacuum Solar Telescope, La Palma, Spain

L. Strous, D. Torgerson, Stanford Lockheed Institute for Solar Research

Stellar Dynamos

DIFFERENTIAL ROTATION + TURBULENT CONVECTIO

$\Rightarrow$ MAGNETIC FIELD GENERATION

FOR SUN - $\alpha\Omega$ dynamo - operating in shear zone at bottom of convection zone

Magnetic flux stored in "undershoot layer"
Convection inhibits magnetic buoyancy.
Strongest field at bottom of CZ - few × 10KG"

"Turbulent" dynamos also operate in Sun and other sta
[α^2]

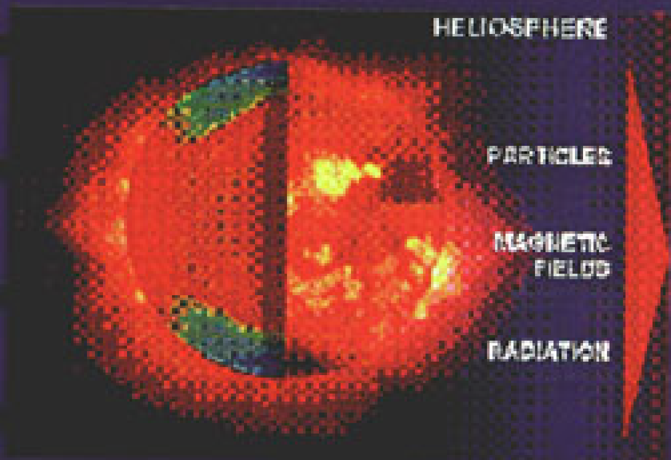
Details of dynamo theory largely untested observational

For Sun theories try to match

- 22yr solar cycle + polarity reversal
- spot migration - "Butterfly Diagram"
- differential rotation
- behavior of emerging field into photosphere

Other stars can show RADICALLY different activity patter

Manifestations and Effects of Stellar Magnetic Activity



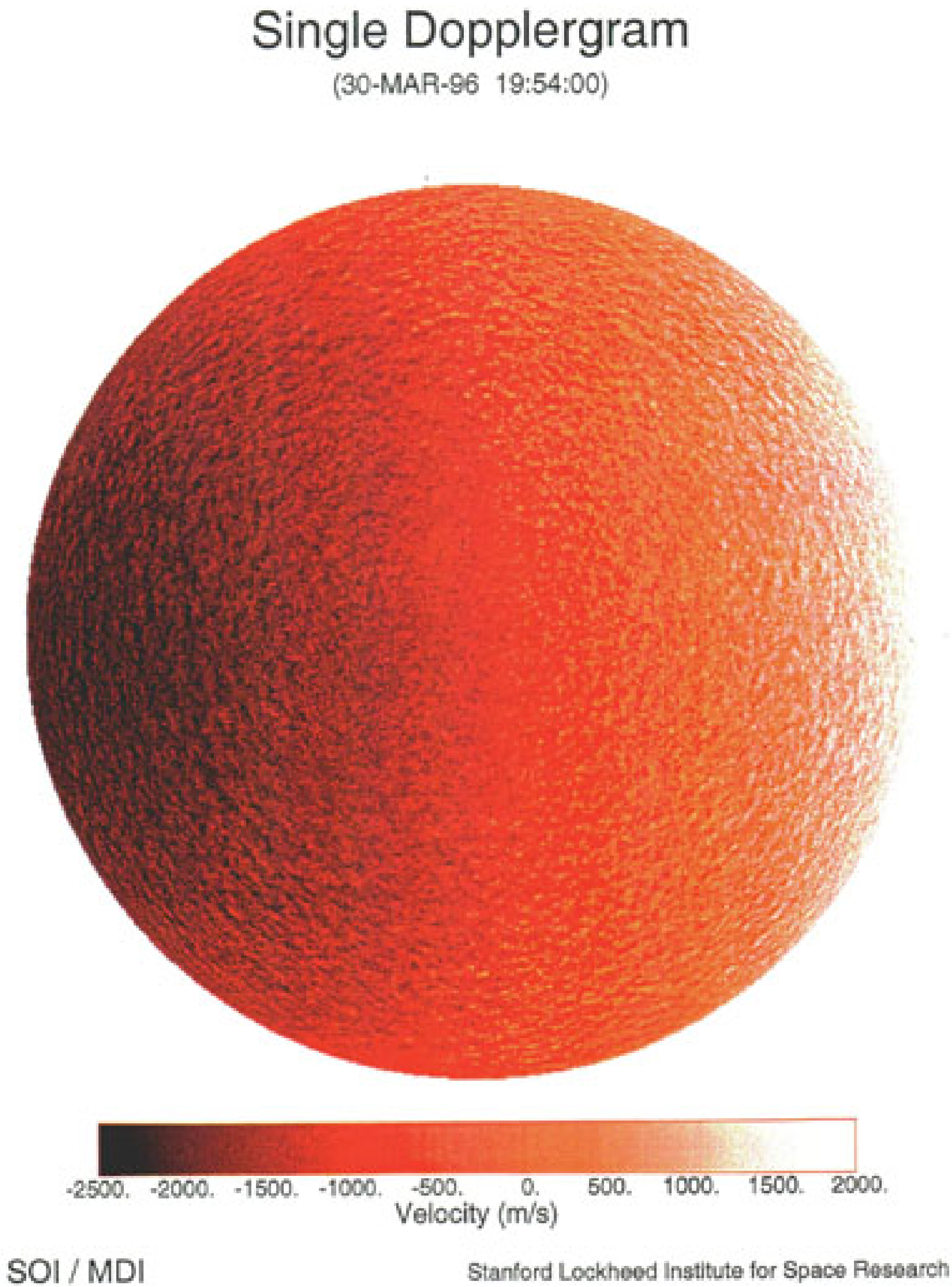
- **Solar luminosity shows cyclic** changes
  - induced climate changes on Earth, such as the 17th-Century Little Ice Age during the solar Maunder minimum
- **In solar/stellar atmospheres:**
  - magnetic regions & star spots;
  - very hot outer atmospheres;
  - explosive flares & high-energy particles and radiation;
  - stellar wind & coronal mass ejections

Stellar Oscillations

Source: *Lecture Notes on Stellar Oscillations*, Jorgen Christensen-Dalsgaard (Aarhus University, Denmark) – http://www.obs.aau.dk/ jcd/oscilnotes/comb-h.tex.ps.gz

MDI Imaging of the Sun

- Single Dopplergram from Michelson Doppler Imager (MDI) on SOHO.
- MDI measures the photospheric radial velocity.
- Dominant effect in single Dopplergram is solar rotation.



MDI Imaging of the Sun

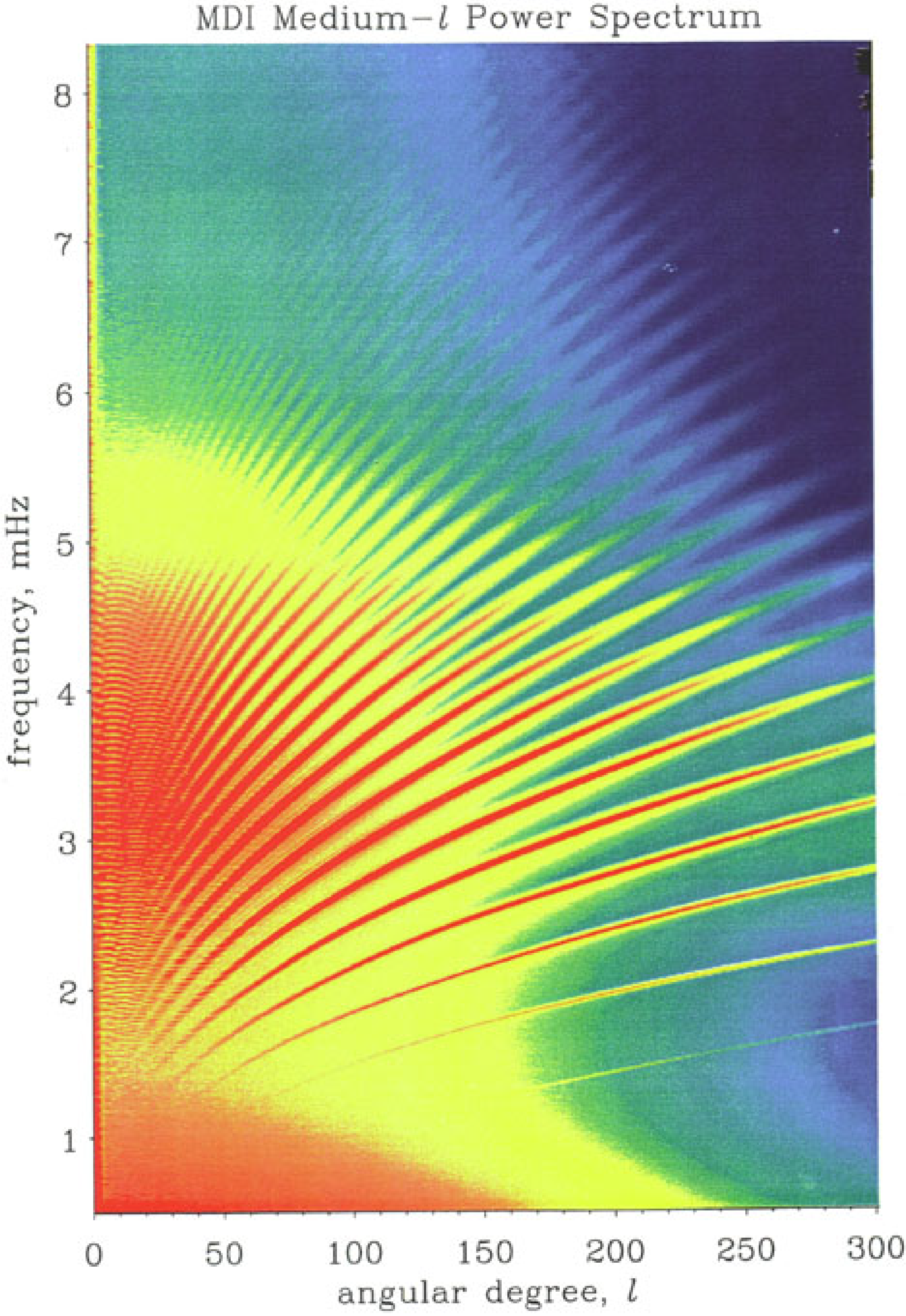
- Subtracting an average Dopplergram (summed over 45 minutes) from a single velocity image reveals the surface motions associated with sound waves traveling through the Sun's interior.
- The smallscale light and dark regions represent the up and down motions near the solar surface.
- The pattern falls off towards the limb because the acoustic waves are primarily radial.

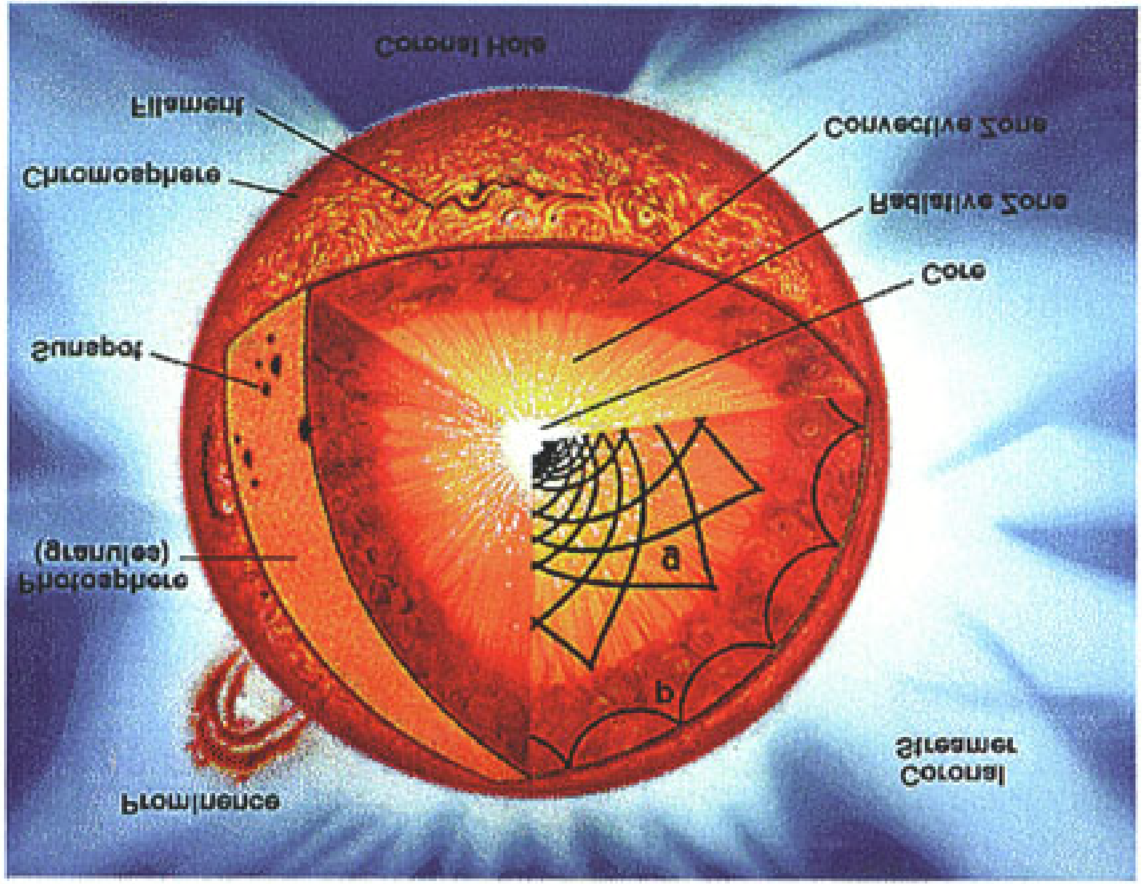
Single Dopplergram Minus 45 Images Average

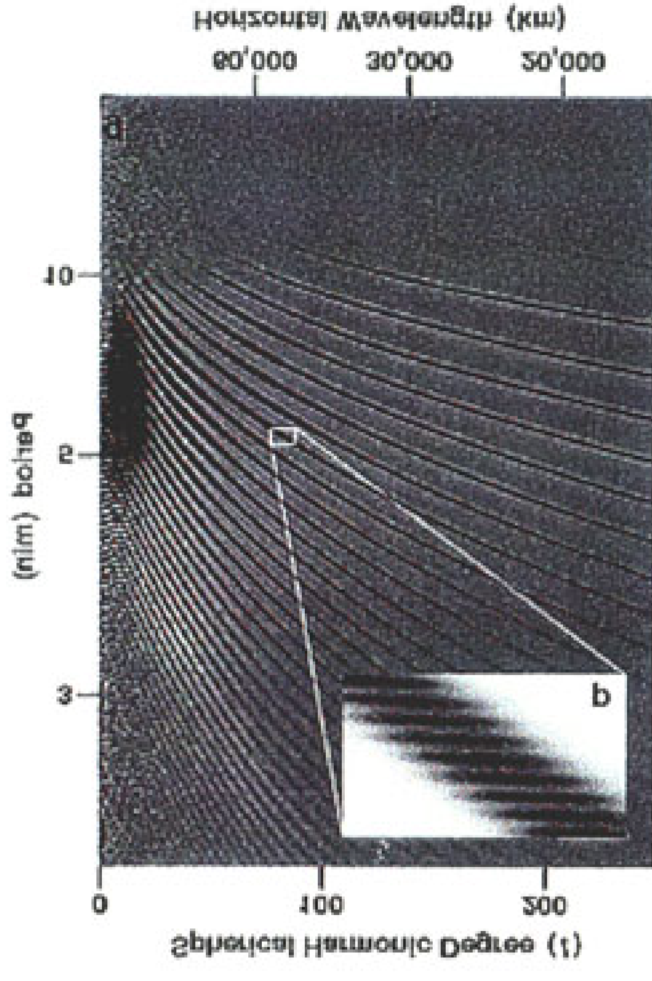
(30-MAR-96 19:54:00)

SOI / MDI

Stanford Lockheed Institute for Space Research


MDI Medium-l Power Spectrum
frequency, mHz
1
2
3
4
5
6
7
8
0
50
100
150
200
250
300
angular degree, l


Coronal Hole
Filament
Chromosphere
Convective Zone
Radiative Zone
Core
Sunspot
Photosphere
(granules)
Prominence
Coronal
Streamer
g
p


Horizontal Wavelength (km)
60,000
30,000
20,000
Period (min)
10
5
3
Temporal Frequency ν (mHz)
0
2
4
6
Spherical Harmonic Degree (l)
0
100
200
a
b

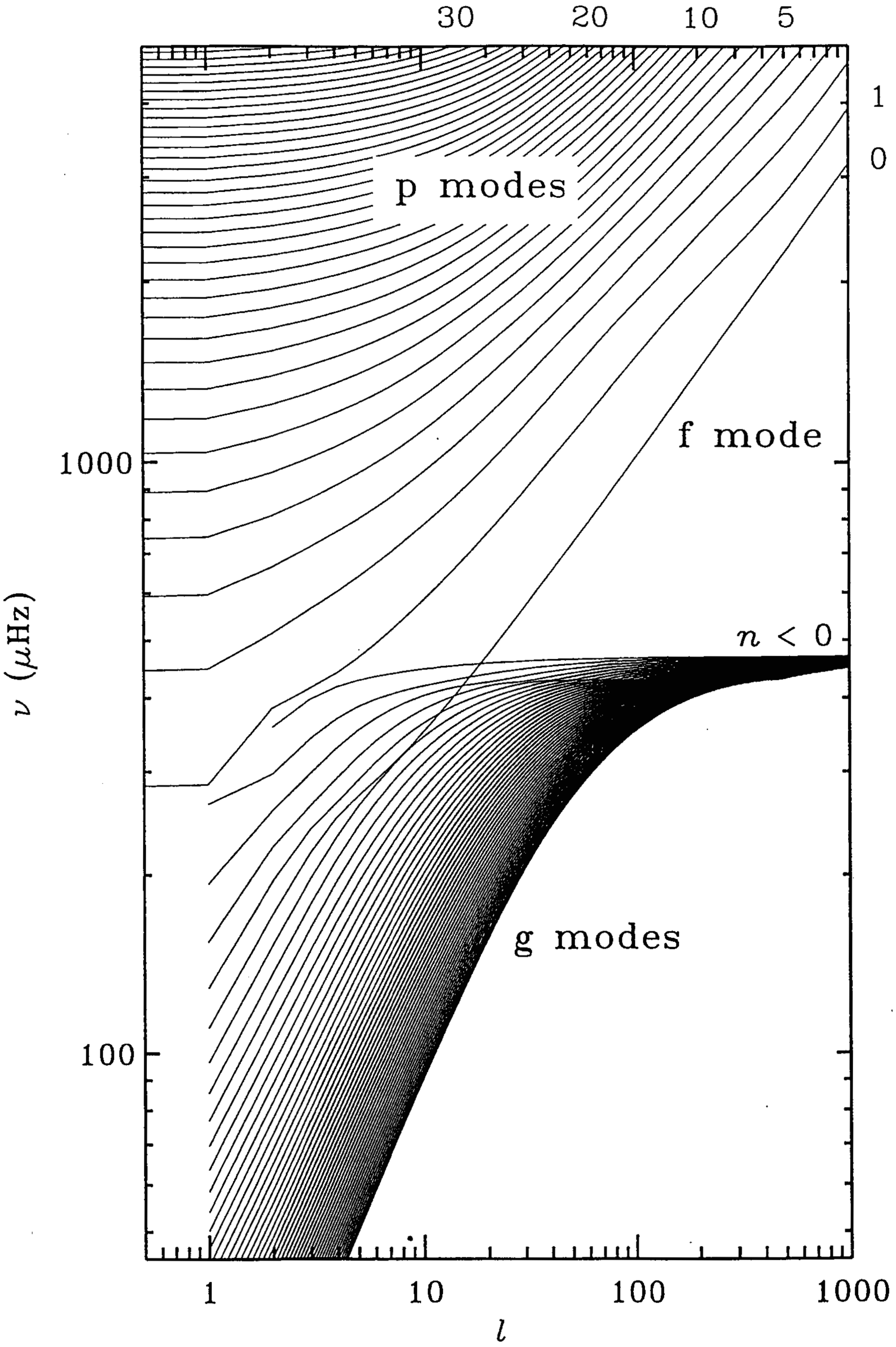


Figure 5.6. Cyclic frequencies $\nu = \omega/2\pi$, as functions of degree l, computed for a normal solar model. Selected values of the radial order n have been indicated.

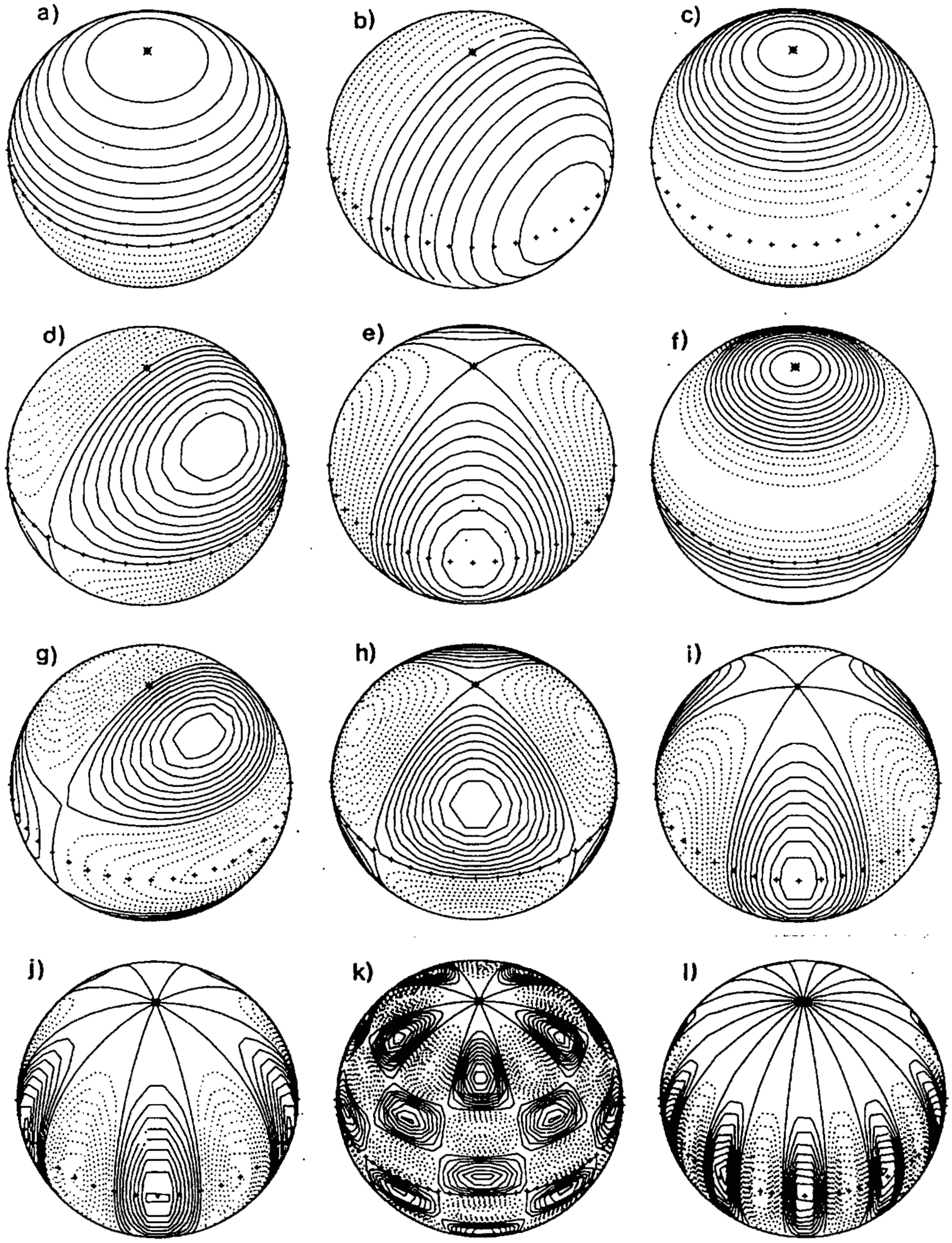
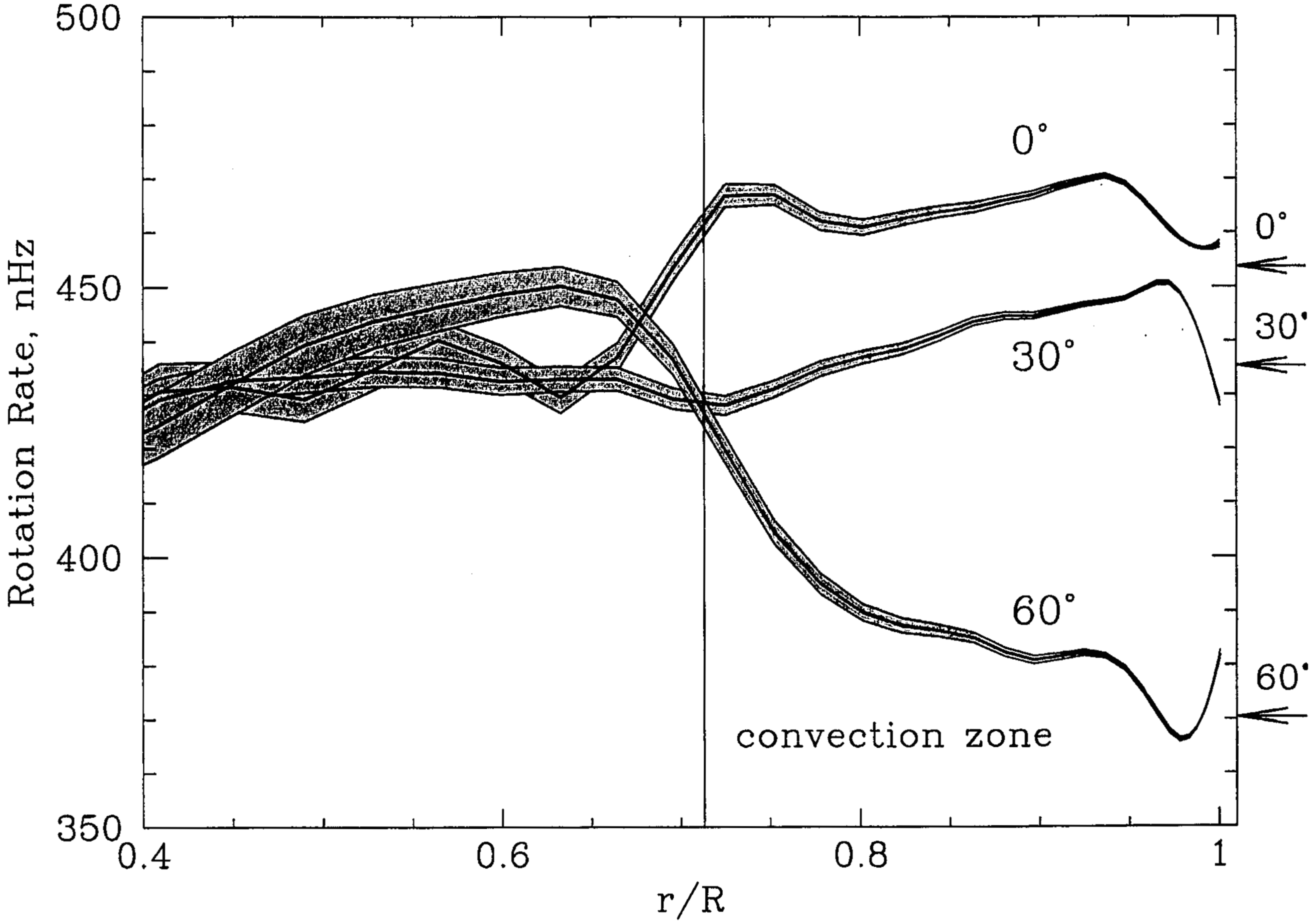


Figure 2.1. Contour plots of the real part of spherical harmonics Y_l^m [*cf.* equation (2.1); for simplicity the phase factor $(-1)^m$ has been suppressed]. Positive contours are indicated by continuous lines and negative contours by dashed lines. The $\theta = 0$ axis has been inclined by 45° towards the viewer, and is indicated by the star. The equator is shown by "++++". The following cases are illustrated: a) $l = 1$, $m = 0$; b) $l = 1$, $m = 1$; c) $l = 2$, $m = 0$; d) $l = 2$, $m = 1$; e) $l = 2$, $m = 2$; f) $l = 3$, $m = 0$; g) $l = 3$, $m = 1$; h) $l = 3$, $m = 2$; i) $l = 3$, $m = 3$; j) $l = 5$, $m = 5$; k) $l = 10$, $m = 5$; l) $l = 10$, $m = 10$.

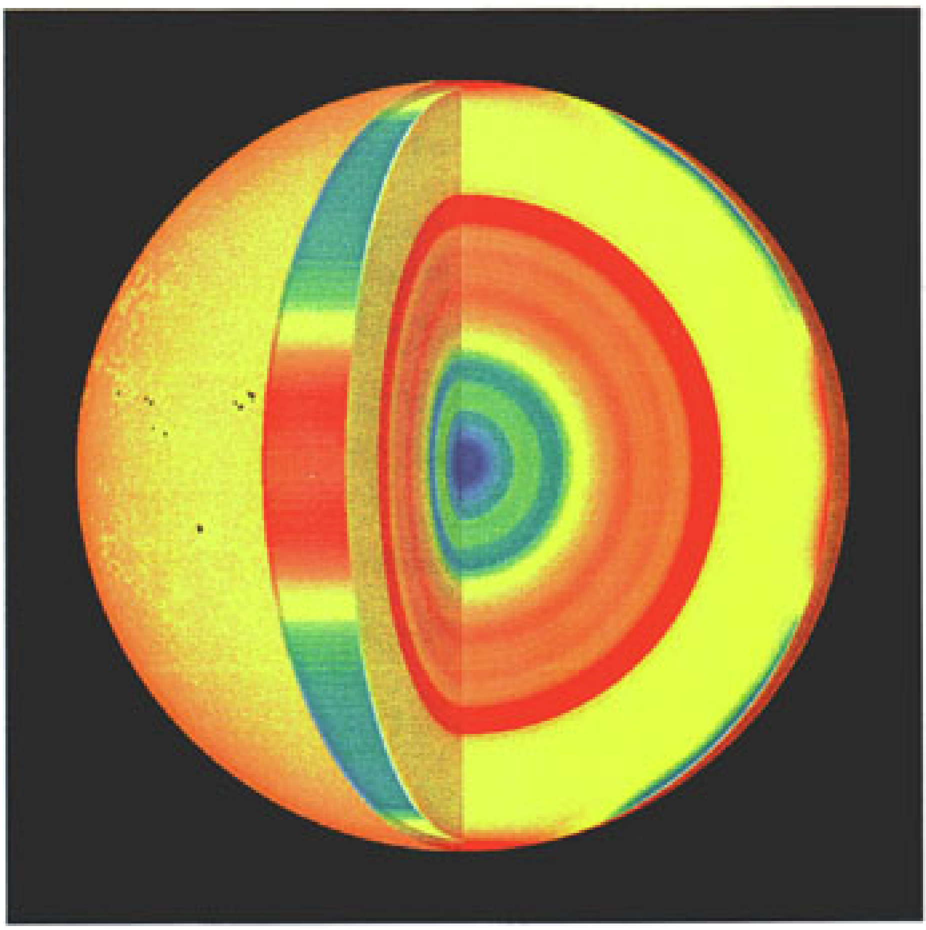
Solar Internal Rotation

- Inferred rotation rate as a function of depth and latitude derived from SOHO helioseismology.
- Convection zone rotates uniformly along a radius with all depths showing the surface differential rotation.
- Below the convection zone is the shear layer of shear connecting to the rigidly rotating radiative core.



Solar Internal Temperature Distribution

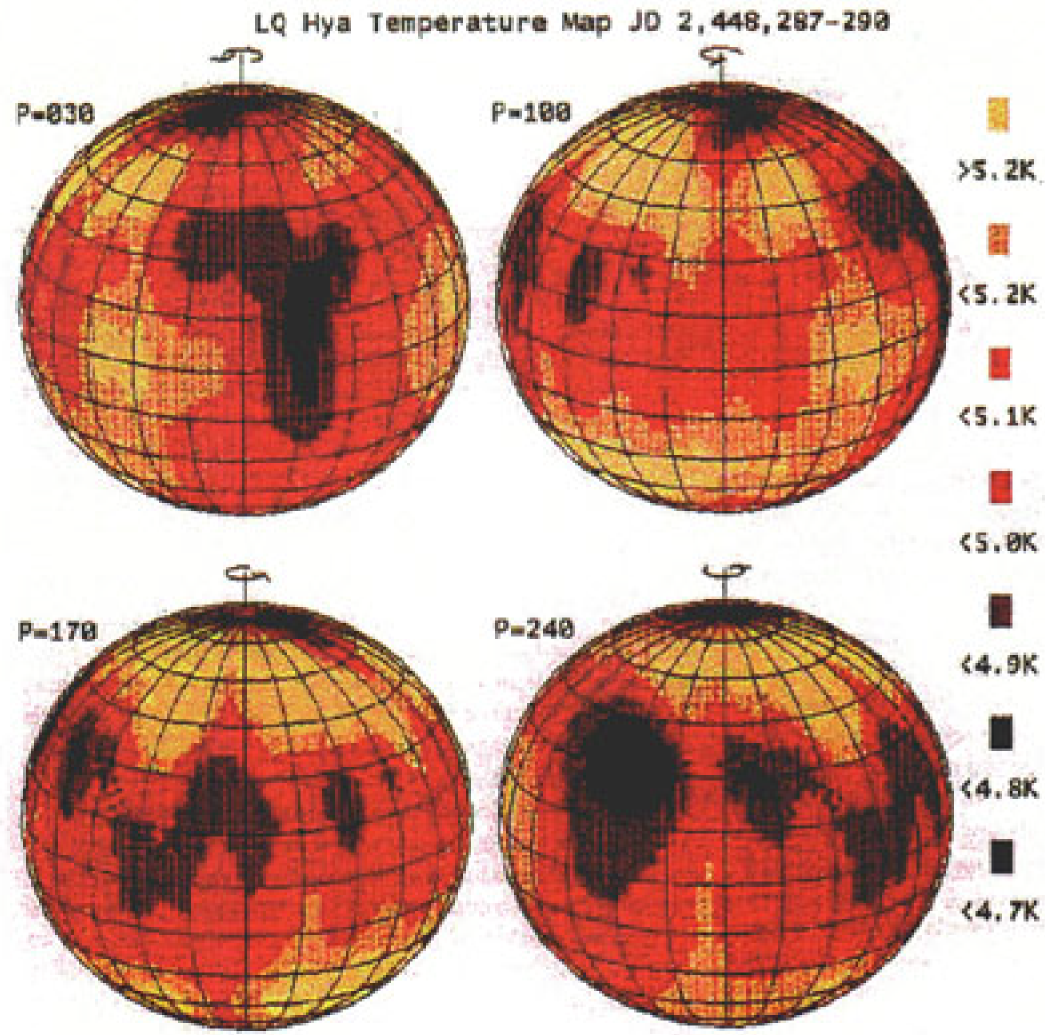
- Red layers - sound travels faster than predicted by the theories, implying that the temperature is higher then expected.
- Blue layers - sound speed (and temperature) is lower than expected.
- Higher temperatures than expected seen at the transition between the convection zone and the radiative core. This shear zone, between the faster-turning outer region and the slower interior, is directly related to generating the magnetic dynamo.
- The core is cooler than predicted by $\sim 0.1\%$. Although the discrepancy may seem small, it implies that the thermonuclear energy generation could be underperforming at present.



[Credit: SOHO (ESA & NASA), MDI/SOI and VIRGO data imaged by A. Kosovichev, Stanford University]

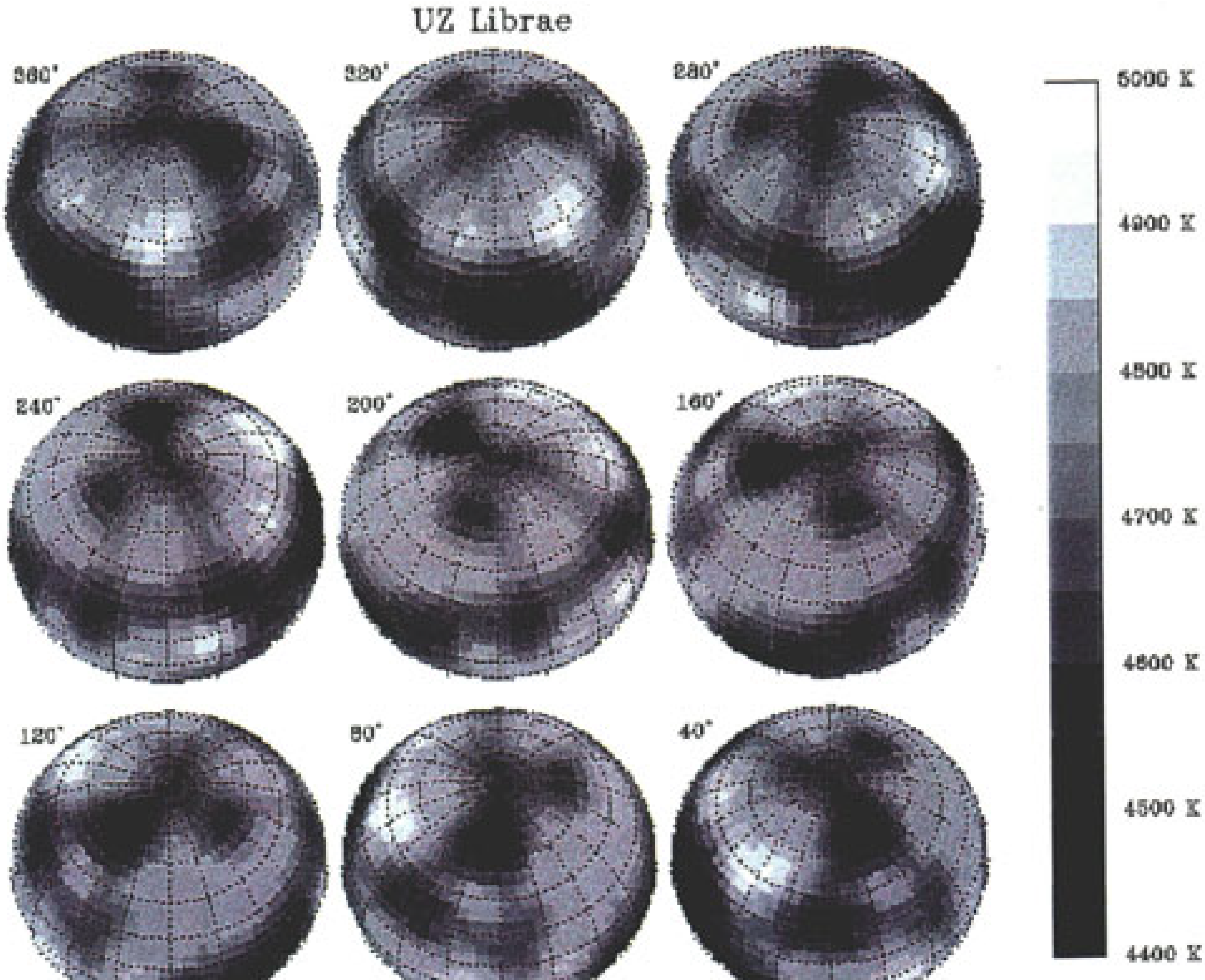
STARSPOTS - Doppler Imaging

Most information on starspot distributions on active stars has come from Doppler Imaging studies. As a starspot moves across the stellar disk it appears as a distinct feature in the optical absorption line spectrum.



STARSPOTS - Doppler Imaging

Doppler images of UZ Lib (K0 III, rotational period 4.7 days) constructed by Strassmeier (1996, A&A 314, 558) based on data from 1994 March. These images show many features typical of active stars: strong photospheric temperature contrasts with cool spots spread over the stellar surface, large spot filling factors, the presence of polar spots.



SURFACE STRUCTURE ON RED SUPERGIANTS

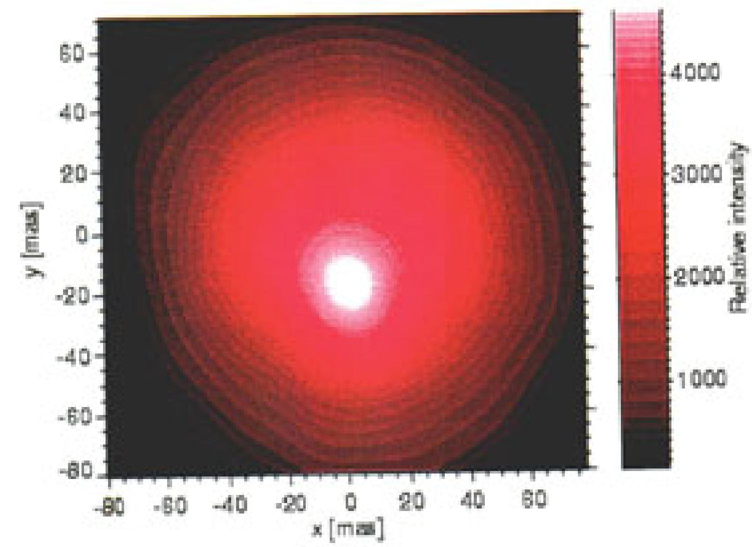
- Red giants and supergiants show only weak magnetic activity.
- Their atmospheres are dominated by wind outflow.
- Do not expect large starspots as on the Sun or active stars.
- Supergiants may show giant convective cells in their photospheres - suggested by Schwarzschild (1975 ApJ 195, 137).

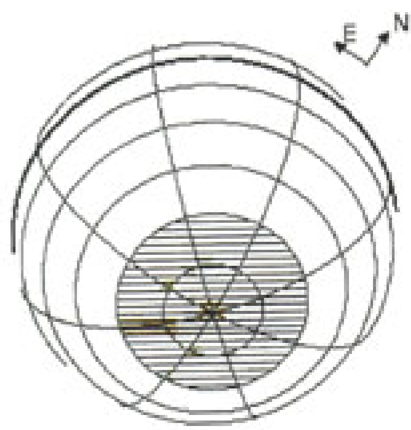
SURFACE STRUCTURE - HST UV Imaging

- HST imaging using FOC and other cameras shows asymmetric ligh distribution in Mg II 2800Å emission (Uitenbroek et al. .
- Size of disk is ~ 2 R_*.
- This emission is being formed in base of wind.

Mg II emission to 270 m
from long slit spect
(GHRS)

1995
March



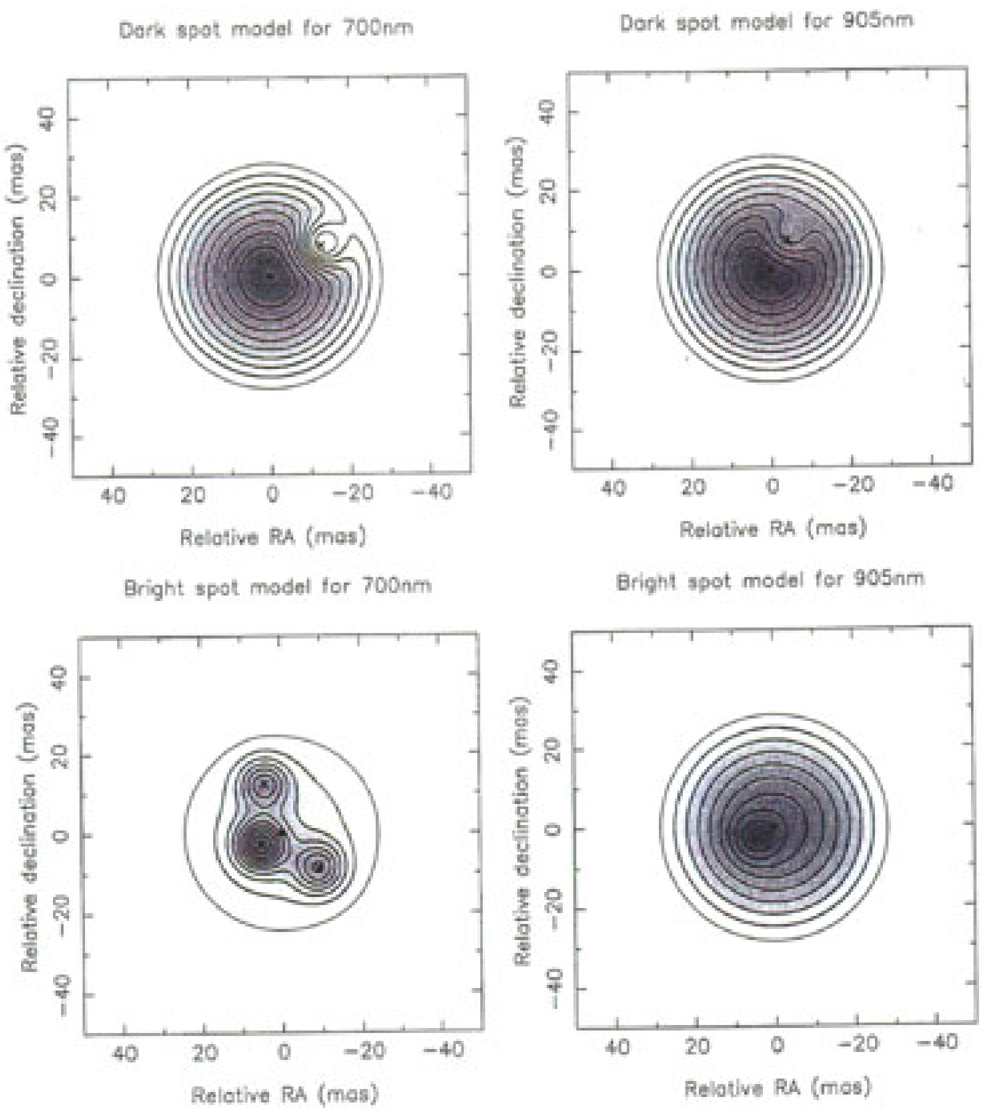


$d = 131$ pc
$R_* \sim 800 R_\odot$

SURFACE STRUCTURE - Optical/IR Interferometry

- Optical interferometry of a range of red supergiants frequently detects asymmetric light distributions - "hot spots".
- "Hot spots" are seen to be time variable and sometimes are not present at all.
- As an example, below, are reconstructed images of Betelgeuse 7000Å and 9050Å (Young et al. 2000 MN 315, 635).
- Presently, it is very unclear whether these correspond in any way to the Schwarzschild convective cells.

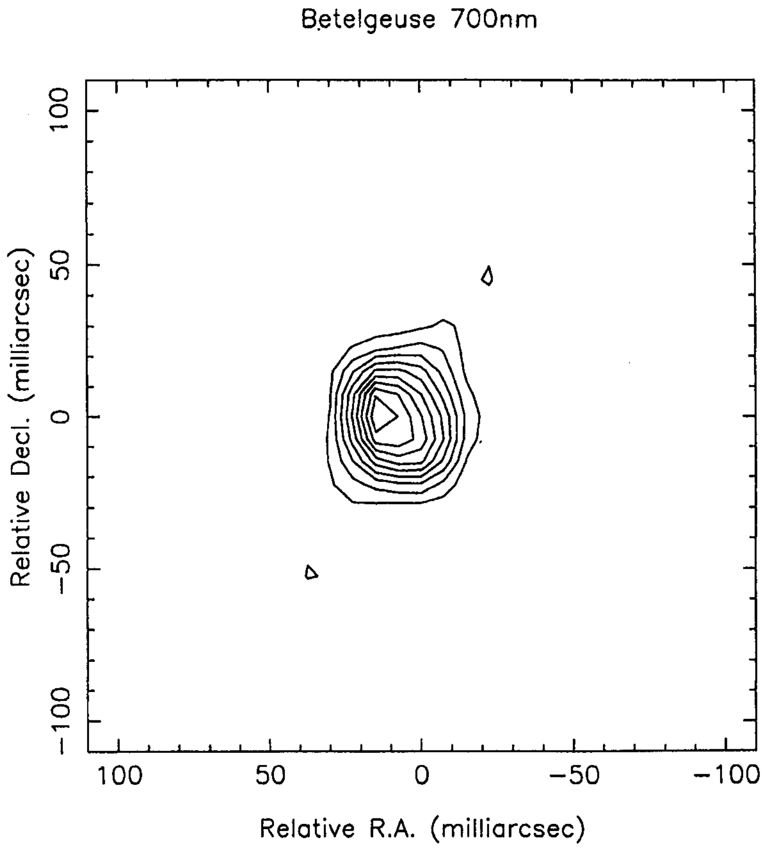
1997
oct/nov



SURFACE STRUCTURE - Aperture Masking

- Non-redunant aperture masking using large telescopes provides similar images.
- Another example of Betelgeuse from Young et al. (2000).

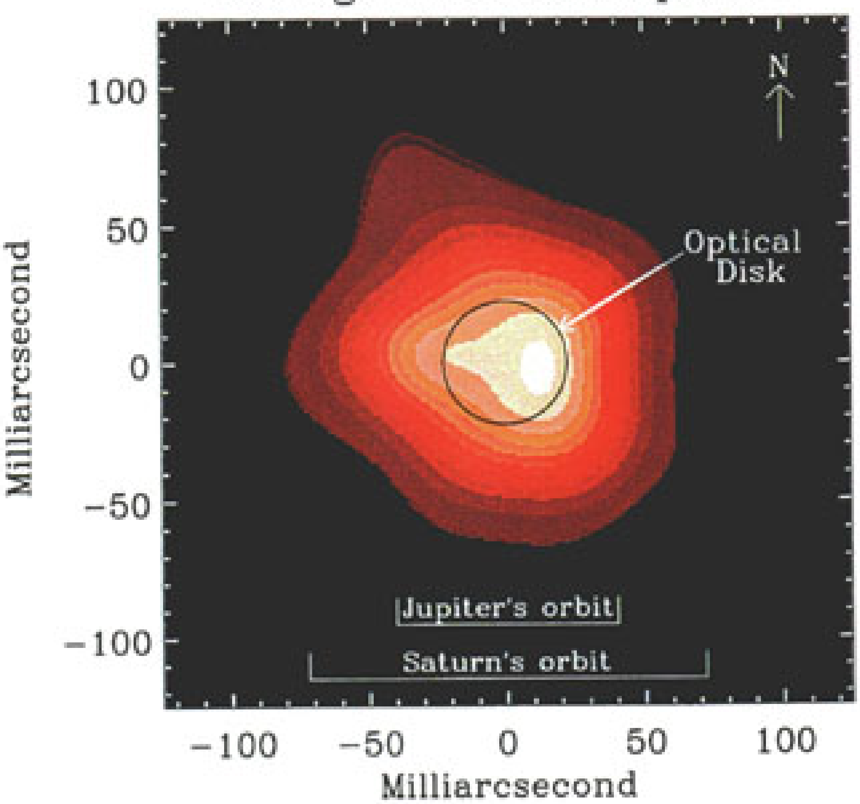
1997
NOV



SURFACE STRUCTURE - Radio Interferometry

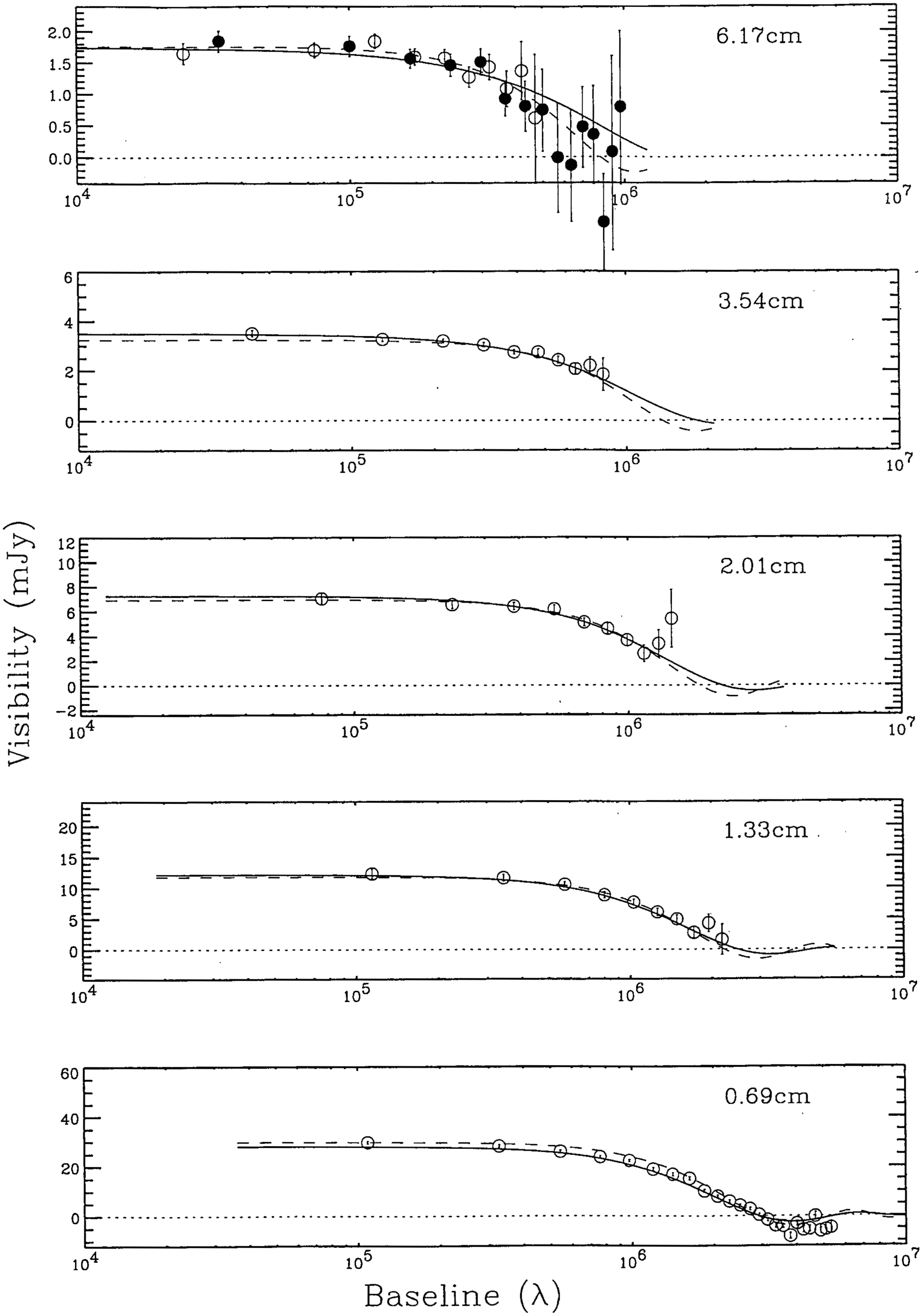
- Radio images of supergiants show nonuniform emission.
- Lim et al. found an asymmetric disk at 7 mm for Betelgeuse.
- This emission is extended and formed in regions of similar size to the UV emission lines.

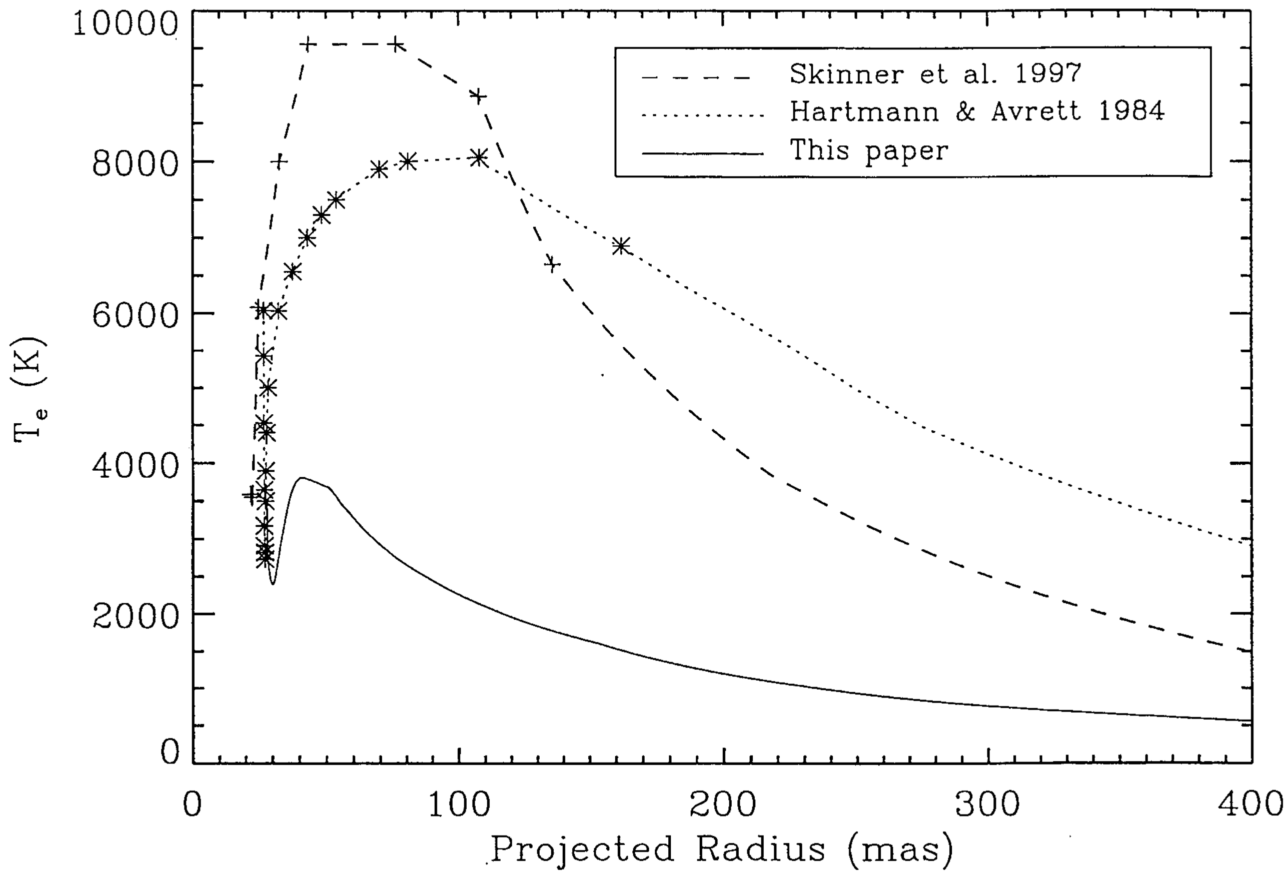
7mm Radio Image of
Betelgeuse's Atmosphere



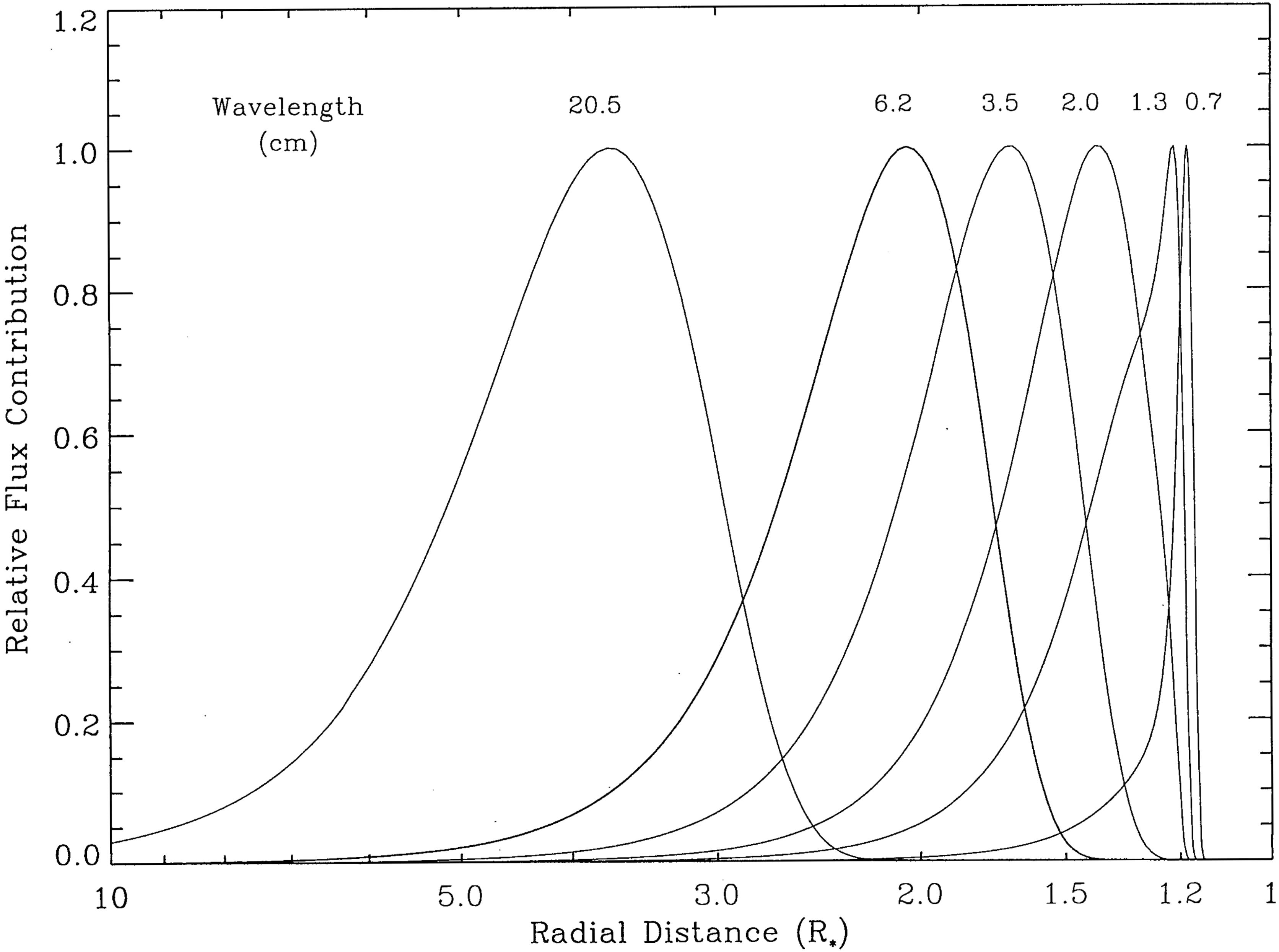
Courtesy of J. Lim, C Carilli, S. M. White,
A. J. Beasley, & R. G. Marson

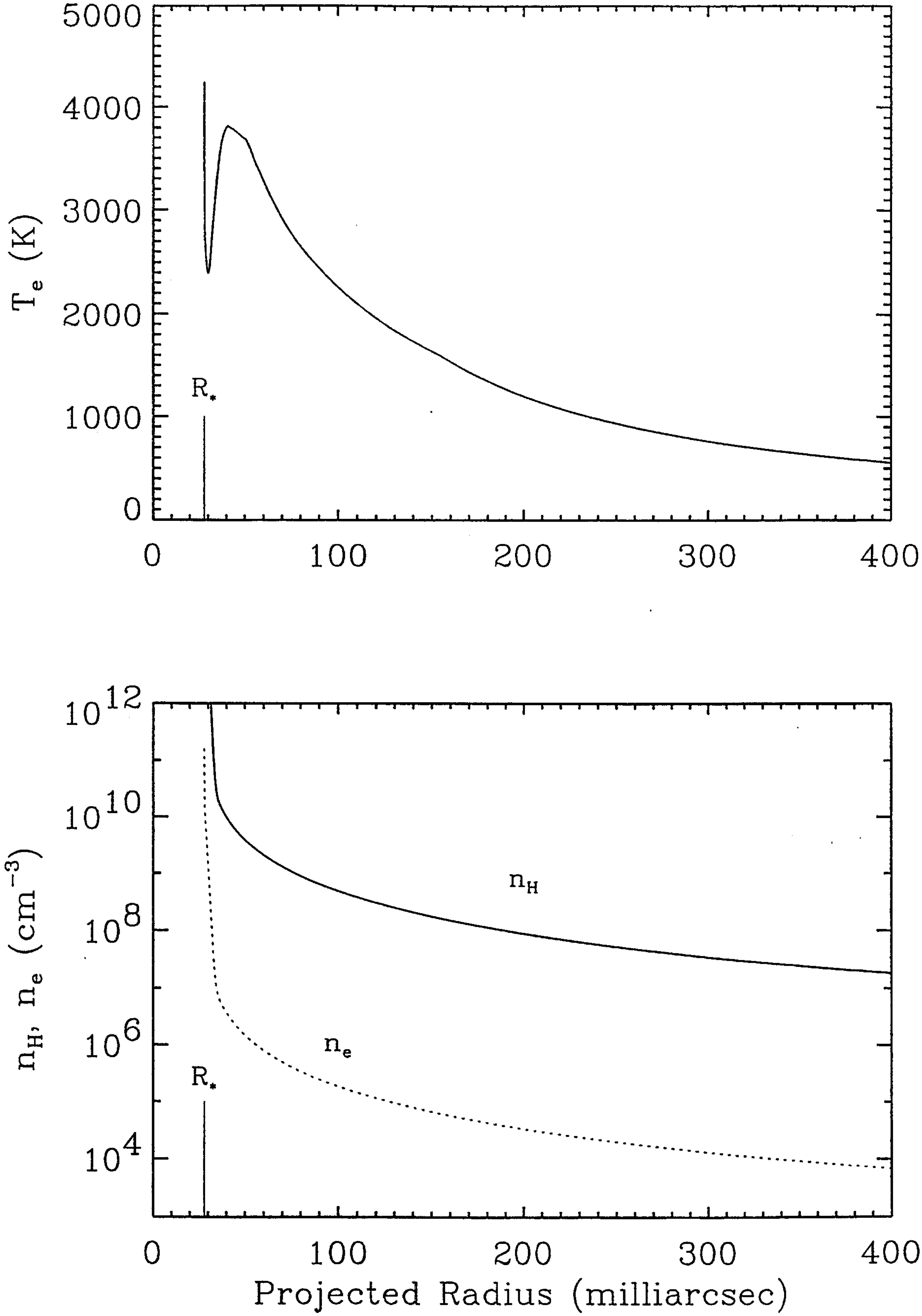
(1998, Nature 392, 575)


6.17cm
3.54cm
2.01cm
1.33cm
0.69cm
Visibility (mJy)
Baseline (λ)



Skinner et al. 1997
Hartmann & Avrett 1984
This paper
T_e (K)
Projected Radius (mas)
0
2000
4000
6000
8000
10000
0
100
200
300
400


Wavelength
(cm)
20.5
6.2
3.5
2.0
1.3
0.7
Relative Flux Contribution
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10
5.0
3.0
2.0
1.5
1.2
1
Radial Distance (R_*)



5000
4000
3000
2000
1000
0
T_e (K)
R_*
0
100
200
300
400
10^{12}
10^{10}
10^8
10^6
10^4
n_H, n_e (cm^{-3})
n_H
n_e
R_*
0
100
200
300
400
Projected Radius (milliarcsec)

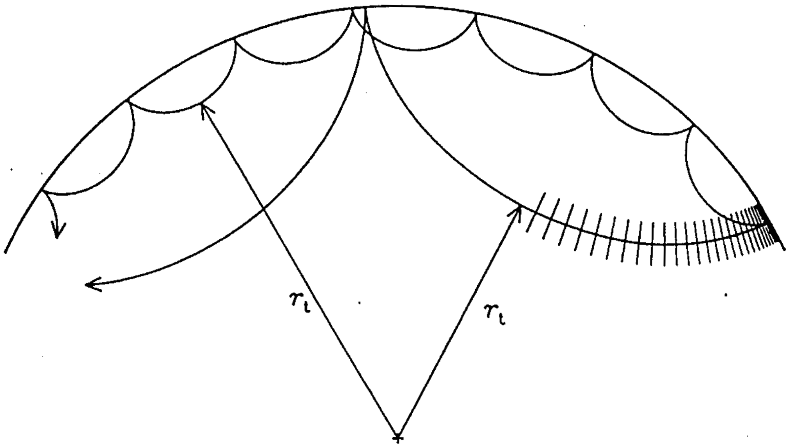


Figure 5.4. Propagation of acoustic waves, corresponding to modes with $l = 30$, $\nu = 3\,\mathrm{mHz}$ (deeply penetrating rays) and $l = 100$, $\nu = 3\,\mathrm{mHz}$ (shallowly penetrating rays). The lines orthogonal to the former path of propagation illustrate the wave fronts.

Stellar angular diameters:

Largest M supergiants ~ 40–60 mas

Largest K giants ~ 20 mas

Active binary primaries ~ 10–20 mas

Nearby dwarf stars ~ few mas